INVESTIGATION OF THE BEHAVIOR FACTOR IN SMA BRACED FRAMES

H.Ghaffarzadeh[1] and A.Mansouri[2]

[1] *Assistant Prof, Dept. of Structural Engineering, University of Tabriz, Tabriz. Iran*
[2] *Structural Engineer, Dept. of Structural Engineering, University of Tabriz, Tabriz. Iran*
Email: ghaffar@tabrizu.ac.ir, alimansr@gmail.com

ABSTRACT :

Shape memory alloys (SMAs) are novel materials with great potential to enhance the performance of civil structures. SMAs have found applications in structural engineering due to their re-centering, high damping capacity, durability and fatigue resistance. Aforementioned characteristics of SMAs rely on two unique properties: shape memory effect (SME) and superelasticity. The results of investigations that carried out on SMA braced frames represent the functionality and viable performance of this bracing system. in this paper, SMA wire braces as seismic resisting members that installed diagonally in the frame structure is utilized and the behavior factor (R) and its components including ductility reduction factor and overstrength factor were evaluated by performing pushover analysis on models. The models are frames with different heights and share of braces. Finally, according to the response curves of pushover analysis the behavior factor (R) proposed for this type of bracing system.

KEYWORDS: Shape Memory Alloys (SMAs), Superelasticity, Shape Memory Effect (SME), Behavior Factor

1. INTRODUCTION

Shape Memory Alloys (SMAs) are a class of alloys with special characteristics not present in other materials that used in structural engineering traditionally. SMAs can recover from large strains through the heating (known as shape memory effect) or removal of stress (known as superelasticity). Furthermore these materials have demonstrated energy dissipation capability, large elastic strain capacity, hysteretic damping, excellent fatigue and corrosion resistance and re-centering capability. For these characteristics SMAs have found applications in many fields especially in structural engineering. In this field they can be used in passive, semi-active and active control of structures to reduce damages and hazards.

Like many other alloys, SMAs have more than one crystal structure or phase. The prevailing crystal structure depends on both temperature and mechanical stress. The stable phase at high temperature and low stresses is called austenite and stable phase at low temperature and high stresses is called martensite. The reversible transformation between austenite and martensite affects all the properties of SMAs. This transformation can be either thermal-induced or stress-induced. Austenite present one crystallographic form but martensite has two forms: single variant (stress-induced) and multiple variant (temperature-induced) (Song *et al.*, 2006).

To date, many types of SMAs have been discovered but among them Nitinol (Ni-Ti) consisted of an equi-atomic composition of Nickel and Titanium possess superior properties and is the most commonly used SMA .

One of the applications of SMAs in passive structural vibration control is SMA-based bracing systems. This idea firstly proposed by Salich (Salich *et al*, 2001). In the past decade many analytical and experimental researches carried out on this system. These studies represent that SMA-based braces enhance the performance of structural system.

In this paper after introduction of SMA behavior and significant characteristics, the behavior factor of RC frame equipped with SMA wires as braces investigate.

2. SOME BASICS ON SHAPE MEMORY ALLOYS

1.2. Phase Transformation

In the stress-free state, SMAs are characterized by the four transition temperature: martensite start (M_s), martensite finish (M_f), austenite start (A_s) and austenite finish (A_f).

An SMA exists in fully martensite state when its temperature is less than M_f and in a fully austenite state when its temperature is greater than A_f .During the phase change from martensite to austenite and vice versa, both martensite and austenite coexist. When SMA heated to A_s ,transformation from martensite to austenite occurs and at A_f transformation is completed. By cooling, Reverse transformation occurs at M_s and it is completed at M_f (Alam *et al*., 2007).

2.2. Superelasticity

In the austenite state ($T \geq A_f$) and at constant temperature, when SMA are loading due to stress-induced conversion of austenite to single-variant martensite, SMA represents a nonlinear behavior. Upon unloading as a result of instability of martensite at zero stress, the reverse transformation from single-variant martensite to austenite occurs. This phenomenon known as superelasticity (Figure 1).

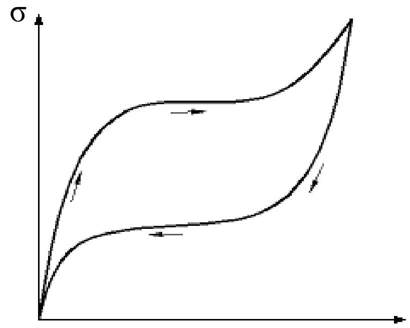


Figure 1 Superelasticity phenomenon (Desroches and Smith, 2003)

3.2. Shape Memory Effect

In the multiple-variant martensite state ($T \leq M_f$), when SMA are loading due to a stress-induced conversion of the multiple-variant martensite to single-variant martensite, the nonlinear behavior occurs. Upon unloading, residual strain remains. This residual strain can be removed by heating the SMA above A_f and then SMA regains its original shape. This phenomenon known as shape memory effect (SME).

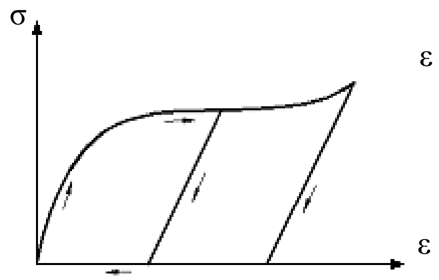
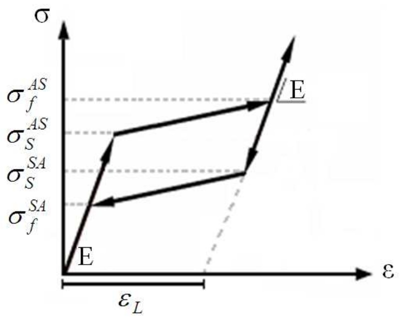


Figure 2 Shape Memory Effect phenomenon (Desroches and Smith, 2003)

3. SMA PROPERTIES IN THIS STUDY

In this study superelastic Nitinol materials were utilized as brace element. The superelastic behavior of the material idealized as shown in figure 3. Mechanical properties of the material have been also shown in Figure 3. The $\sigma_S^{AS}, \sigma_f^{AS}$, σ_S^{SA} and σ_f^{SA} in the figure represent austenite to martensite starting stress, austenite to martensite finishing stress, martensite to austenite starting stress and martensite to austenite finishing stress, respectively.



E^{SMA} [kg/cm²]	275790
σ_S^{AS} [kg/cm²]	4140
σ_f^{AS} [kg/cm²]	5500
σ_S^{SA} [kg/cm²]	3900
σ_f^{SA} [kg/cm²]	2000
ε_L [%]	3.5

Figure 3 Idealized superelastic behavior and its parameters (Auricchio *et al*., 2006)

4. BEHAVIOR FACTOR

Behavior factor is the ratio of the strength required to maintain the elastic to the inelastic design strength of the structure. ATC-19 (ATC-19, 1995) proposed a simplified method to estimate the behavior factor in which, R, is calculated as a product of three parameters:

$$R = R_\mu R_o R_r \tag{4.1}$$

Where, R_μ is the ductility factor, R_o is the overstrength factor and R_r is the redundancy factor. The parameter of R_r, represent the reliability of the structure. In this study, R_r is assumed to be equal to 1.0. R_μ is estimated by relations proposed by Newmark and Hall (1982) and Miranda and Bertero (1994) as follows:

Newmark and Hall:

$$\begin{aligned} R_\mu &= 1 & T &< 0.03s \\ R_\mu &= \sqrt{2\mu - 1} & 0.12 < T &< 0.5 \\ R_\mu &= \mu & T &> 1 \end{aligned} \tag{4.2}$$

Miranda and Bertero in rock sites:

$$\begin{gathered} \phi = 1 + \frac{1}{T(10-\mu)} - \frac{1}{2T} e^{-1.5[\ln(T)-0.6]^2} \\ R_\mu = \frac{\mu - 1}{\phi} + 1 \end{gathered} \tag{4.3}$$

ϕ is a variable for concerning the soil conditions and μ is ductility ratio obtained by dividing roof displacement at the limit state by the yield displacement.

5. DESIGN OF MODELS

To evaluate the behavior factor and its components in SMA braced RC frames, 4-, 8-, and 12-storey frames are considered. These are typical numbers of storey used by some other investigators to cover low- to medium-rise framed buildings (Maheri, 2003). The storey height and bay length of models are fixed to 3m and 5m, respectively. In all frames the mid-bay is braced with superelastic SMA wires diagonally. Figure 4 shows the configurations of the models.

Using SMA in RC frame makes a dual structural system. An important key in dual systems is the share of bracing from lateral load. To investigate the effect of this parameter four different shares from base shear of 0, 25, 50 and 75% for braces were considered. Consequently, braces designed to resist the above shares and RC frames were designed for the remain of base shear in each models. The values of base shear were computed base on Iranian seismic design code No.2800 (2005), zone II. Since the R factor for the braced frames is unknown value, base shears were calculated using $R=6$ for all models. The moment resisting RC frames of the models were also designed in accordance with ACI 318-99 code provisions (1999) considering intermediate ductility specifications. The diameter of braces was calculated base on SMA characteristics shown in figure 3. It is assumed that brace members act as pin-end cable element. The cross section area of SMA braces are calculated and shown in table 5.1.

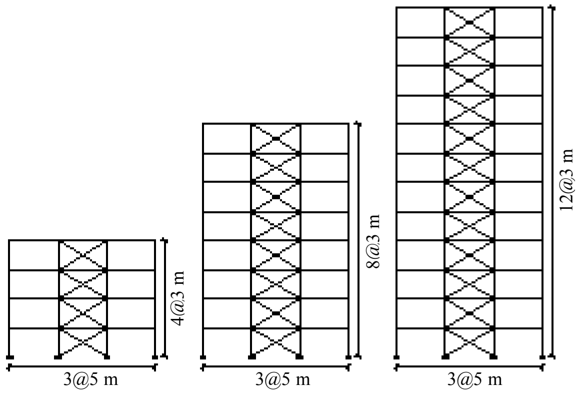


Figure 4 Elevation of frames and configuration of braces

Table 5.1. Area of braces cross section (cm^2)

	Share of braces (%)	1	2	3	4	5	6	7	8	9	10	11	12
4 storey	25	3.7	3.26	2.48	1.33								
	50	7.18	6.41	5.0	2.64								
	75	10.4	9.3	7.11	3.84								
8 storey	25	7.11	6.9	6.44	5.78	4.94	3.91	2.7	1.34				
	50	10.74	10.4	9.74	8.8	7.54	6.0	4.2	2.11				
	75	15.54	15.07	14.13	12.76	10.97	8.75	6.11	3.07				
12 storey	25	10.70	10.53	10.21	9.76	9.15	8.40	7.51	6.52	5.40	4.16	2.80	1.36
	50	13.18	13.0	12.60	12.04	11.32	10.41	9.35	8.11	6.72	5.23	3.57	1.74
	75	19.34	19.07	18.52	17.70	16.70	15.32	13.8	12.0	10.0	7.80	5.31	2.60

6. NONLINEAR STATIC ANALYSIS OF MODELS

For evaluating the R factor and its components, nonlinear static analysis (pushover analysis) was developed to

determine structural response curves. The nonlinear static analysis is an incremental iterative method to obtain the base shear versus roof displacement (as a control point) of a structure. The inverse triangular load distribution was adopted for the pushover analysis in this study. The OpenSEES V.2.0 (Open System for Earthquake Engineering Simulation) program (Mazzoni et al., 2007) was implemented to computer modeling of the frames. The OpenSEES is a general linear and nonlinear analysis of the structures. The superelastic behavior modeling of SMAs has been implemented in version as well on the basis of Auricchio, Sacco (Auricchio, 1997) and Fugazza (Fugazza ,2003) models.
The uniaxial material *concrete03* and *steel02* were chosen for modeling the concrete and reinforcement material such a way the post-yield stiffness in steel was considered 5% of initial stiffness. In each models gravity loads considered as total of dead loads and 20% of live loads. Displacement control based pushover analysis of the models by considering P-Δ effect was performed. The capacity curves of the models were plotted to show the effect of SMA wires on the RC frames. Figure 5a, 5b and 5c shows the results of pushover analysis. It can be observed that when the share of braces increases the strength of frame was increasing.

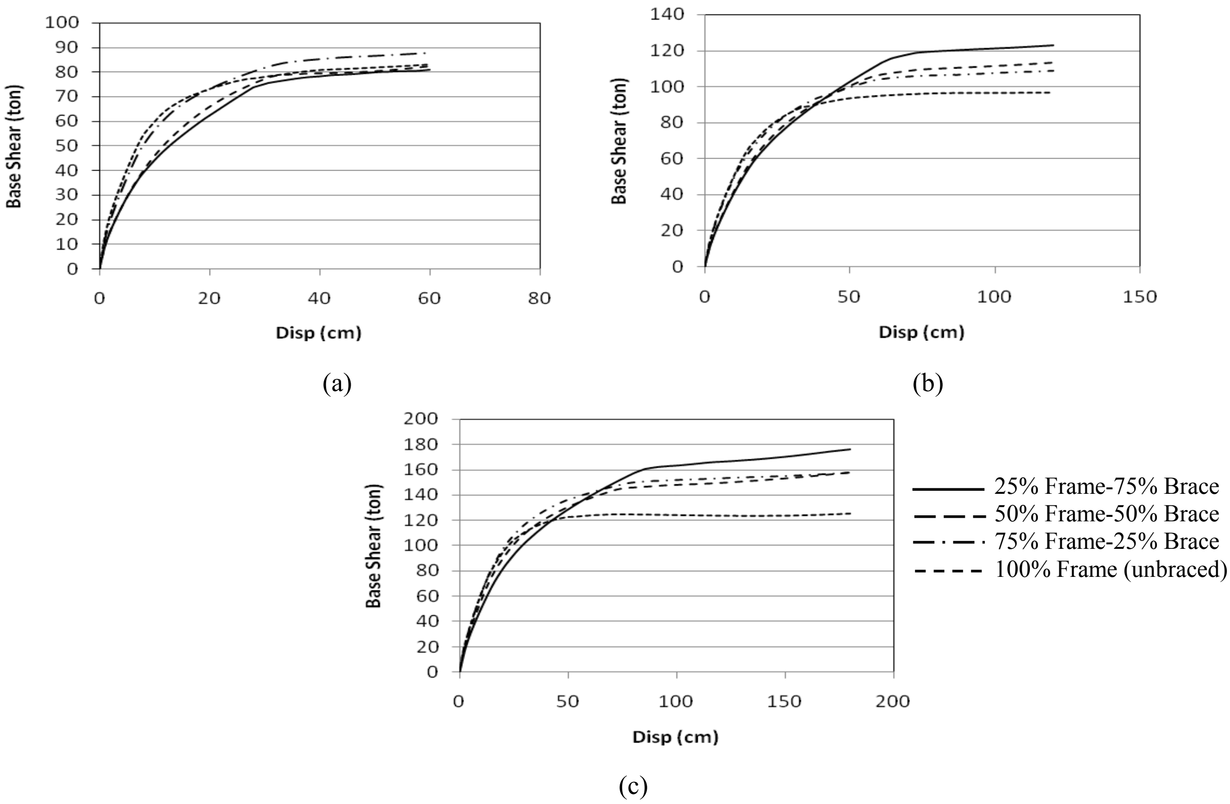


Figure 5 Pushover curves: (a) 4-storey (b) 8-storey (c) 12-storey

7. OVERSTRENGTH FACTOR (R_s)

To investigate the overstrength factor (R_s), the capacity curves which obtained from pushover analysis were used. Each curve idealized as recommended in FEMA-356 (2000) in such a way that the area under the original curves is equal to one that idealized as bilinear straight lines. The overstrength factor was determined as the ratio of the yield strength to the design strength of each model. Figure 6 shows the variation of the overstrength factor by the share of braces and storey. It can be seen that by increasing the brace shares, the overstrength factor tend to rise.

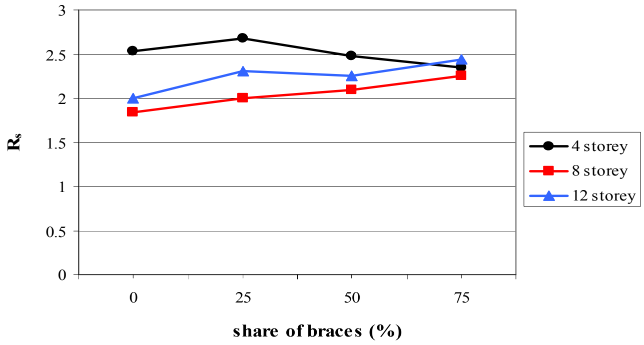
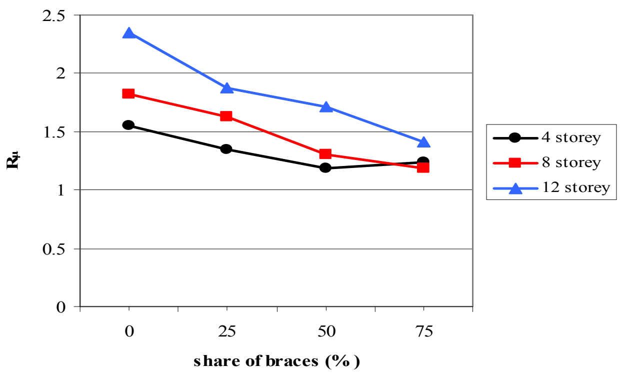


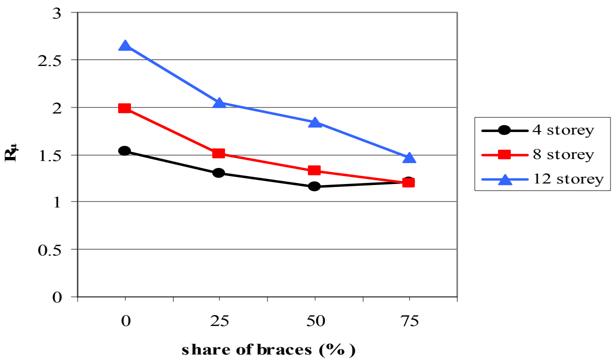
Figure 6 variation of overstrength factor

8. DUCTILITY FACTOR (R_μ)

The ductility factor of the models was also calculated using the relation proposed by Newmark-Hall and Miranda-Bertero. According to the equation 4,2 and 4.3 the ductility factor is depend on the ductility ratio. Ductility ratio is inherent characteristic of the structural system which obtained by dividing roof displacement at the limit state by the yield displacement. Due to large deformation capacity of the SMA wires, the ductility ratio was evaluated in two maximum displacement levels, maximum roof displacement of 2% of frame height and 2.5%. Figure 7 and 8 show the variation of ductility factor, R_μ, for models when maximum roof displacement reaches to 2% and 2.5% of structures height, respectively. It can be seen that by increasing the number of storey, R_μ increase. Moreover, by increasing the share of braces, R_μ decrease. It is also observed that, ductility factor calculated by Miranda-Bertero equation is more than that one obtained by Newmark-Hall equation in 8- and 12-storey frames.

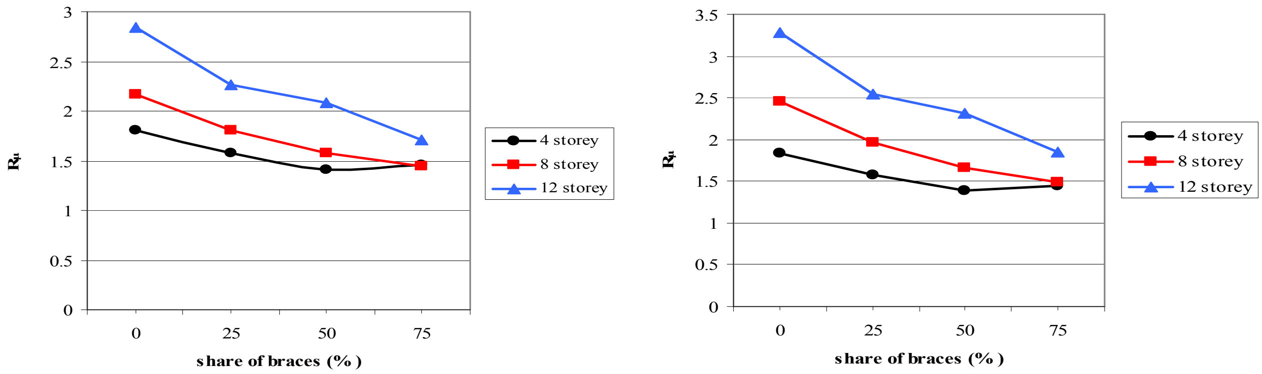


(a) Newmark and Hall



(b) Miranda and Bertero

Figure 7 Variation of ductility factor , Δ_{max}= 0.02H

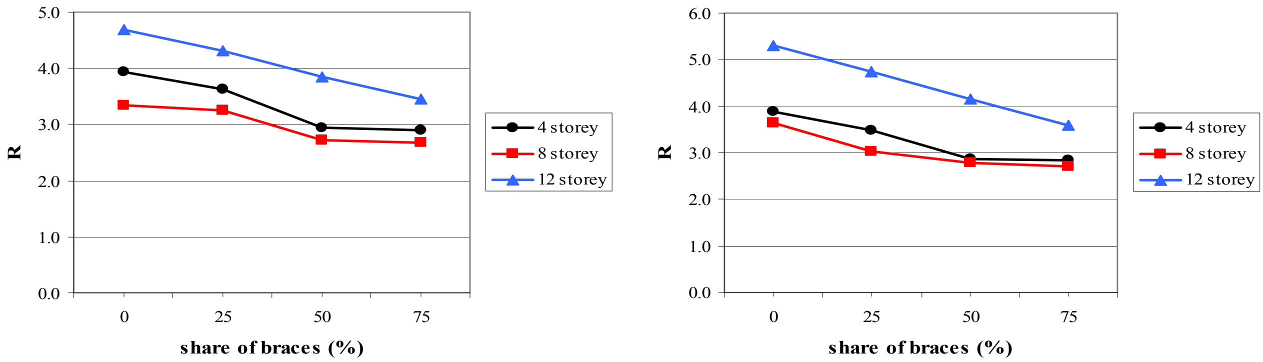


(a) Newmark and Hall (b) Miranda and Bertero

Figure 8 Variation of ductility factor, Δ_{max}= 0.025H

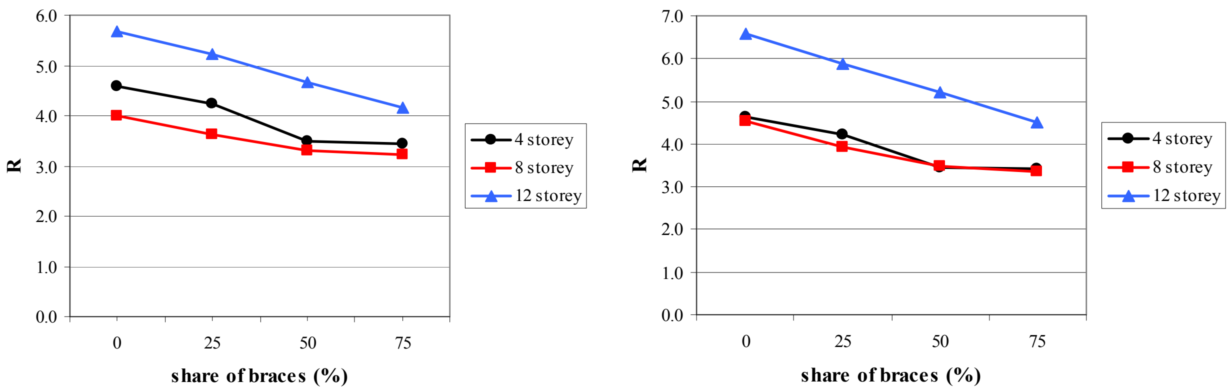
9. BEHAVIOR FACTOR

The behavior factor, are computed by multiplying the overstrength and ductility factors that represented in figures (6), (7) and (8). The results of this computation represented in Figure 9 and 10. It is obviously observed that the behavior factor obtained by Miranda and Bertero is higher than one obtained by Newmark and Hall. Furthermore, the results show that the behavior factor decreased as the share of brace increases.



(a) Newmark and Hall (b) Miranda and Bertero

Figure 9 Variation of behavior factor when Δ_{max}= 0.02H



(a) Newmark and Hall (b) Miranda and Bertero

Figure 10 Variation of behavior factor when Δ_{max}= 0.025H

10. CONCLUSION

In this study the behavior factor and its components, overstrength and ductility factors, were evaluated for three type of storey and four type of SMA brace shares. To obtain the capacity curves, the nonlinear static analysis was carried out and idealized curves were used to determine the behavior factor components. The results of this study can be summarized as follows:

1. It can be seen that by increasing the brace shares, the overstrength factor, R_s tend to rise.
2. By increasing the number of storey, ductility factor, R_μ, was increased. This results are more obvious for the results obtained from Miranda-Bertero equation than that one calculated by Newmark-Hall equation.
3. When the share of braces increase, the ductility factor, R_μ tend to decrease.
4. The behavior factor obtained by Miranda and Bertero is higher than one obtained by Newmark and Hall.
5. The behavior factor decreased as the share of braces increase.

REFERENCES

ACI Committee 318. (1999). Building code requirements for structural concrete (ACI 318-99) and commentary (ACI 318R-99), American concrete institute, P.O. box 9094, Farmington Hills, Michigan.

Alam, MS., Yousef, MA. and Nehdi, M. (2007). Utilizing shape memory alloys to enhance the performance and safety of civil infrastructure: A review. *Canadian Journal of Civil Engineering* **34**, 1075-1086.

ATC. Structural response modification factors. (1995). ATC-19, Applied Technology Council, Redwood City, California, 5–32.

Auricchio, F., Fugazza, D. and Desroches, R. (2006). Earthquake performance of steel frames with Nitinol braces. *Journal of Earthquake Engineering* **10:1**, 1-22.

Auricchio, F., Sacco, E. (1997). A one-dimensional model for superelastic shape-memory alloys with different elastic properties between austenite and martensite. *International Journal of Non-Linear Mechanics* **32**, 1101-1114.

Desroches, R. and Smith, B. (2003). Shape memory alloys in seismic resistant design and retrofit: a critical review of their potential and limitations. *Journal of Earthquake Engineering* **7:3**, 1-15.

FEMA. Prestandard and commentary for the seismic rehabilitation of building. (2000). FEMA-356, Federal Emergency Management Agency, Washington, D.C.

Fugazza, D. (2003). Shape memory alloy devices in earthquake engineering : mechanical properties, constitutive modeling and numerical simulations. Rose School MSc Dissertation, under the supervision of Prof F.Auricchio, A.Pavase and L.Petrini; Pavia, Italy.

Iranian code of practice for seismic resistance design of buildings. (2005). Standard No. 2800. Third edition. BHRC publication No. S-253.

Maheri, MR. and Akbari, R. (2003). Seismic behavior factor, R, for steel X-braced and knee-braced RC building. *Journal of Engineering Structures* **25**, 1505-1513.

Mazzoni, S., McKenna, F., Scott, M., Fenves, G. L. and Jeremic, B. (2007). Open System for Earthquake Engineering Simulation (OpenSEES) — Command Language Manual.

Miranda, E. and Bertero, VV. (1994). Evaluation of strength reduction factors forearthquake-resistant design. *Earthquake Spectra* **10:2**, 357–79.

Newmark, NM. and Hall, WJ. (1982). Earthquake spectra and design. EERI Monograph Series, Oakland (CA): Earthquake Engineering Research Institute.

Salichs, J., Hou, Z. and Noori M. (2001). vibration suppression of structures using passive shape memory alloy energy dissipation devices. *Intelligent Material Systems and Structures* **12**, 671-680.

Song, G., Ma, N. and Li H. (2006). Applications of shape memory alloys in civil structures. *Journal of Engineering Structures* **28**, 1266-1274.